

Low metallicity and ultra-luminous X-ray sources in the Cartwheel galaxy

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20 February 2009

ABSTRACT

Low-metallicity ($Z \lesssim 0.05 Z_{\odot}$) massive ($\gtrsim 40 M_{\odot}$) stars might end their life by directly collapsing into massive black holes (BHs, $30 \lesssim m_{\text{BH}}/M_{\odot} \lesssim 80$). More than $\sim 10^5$ massive BHs might have been generated via this mechanism in the metal-poor ring galaxy Cartwheel, during the last $\sim 10^7$ yr. We show that such BHs might power most of the ultra-luminous X-ray sources (ULXs) observed in the Cartwheel. We also consider a sample of ULX-rich galaxies and we find a possible anti-correlation between the number of ULXs per galaxy and the metallicity in these galaxies. However, the data are not sufficient to draw any robust conclusions about this anti-correlation, and further studies are required.

Key words: black hole physics – galaxies: individual: Cartwheel – X-rays: binaries – X-rays: galaxies – galaxies: starburst

1 INTRODUCTION

Ultra-luminous X-ray sources (ULXs, see Mushotzky 2004 for a review, and references therein) are defined as point-like sources with isotropic X-ray luminosity $L_X \gtrsim 10^{39}$ erg s^{−1}, that is higher than the Eddington luminosity for a $\sim 7 M_{\odot}$ black hole (BH). Most of the brightest ULXs are located in starburst galaxies (Irwin, Bregman & Athey 2004). The origin of ULXs is still an open question. Many different scenarios have been proposed. ULXs could be associated with high-mass X-ray binaries (HMXBs) powered by stellar-mass BHs with anisotropic X-ray emission (e.g. King et al. 2001) or with super-Eddington accretion rate/luminosity (e.g. Begelman 2002) or with a combination of the two mechanisms (e.g. King 2008). ULXs could also be associated with HMXBs powered by intermediate-mass BHs (IMBHs), i.e. BHs with mass $100 M_{\odot} \leq m_{\text{BH}} \leq 10^5 M_{\odot}$ (see van der Marel 2004 for a review). However, IMBH masses larger than $100 M_{\odot}$ are not needed to explain the observational properties of most of ULXs (e.g. Gonçalves & Soria 2006). IMBHs may be required only to explain the properties of some peculiar ULXs, such as the brightest (i.e. the $\lesssim 4$ ULXs with $L_X \gtrsim 10^{41}$ erg s^{−1}), those which show quasi-periodic oscillations (M82 X-1, see Strohmayer & Mushotzky 2003, and NGC 5408 X-1, see Strohmayer et al. 2007) or which are surrounded by isotropically ionized nebulae (e.g. Kaaret, Ward & Zezas 2004).

The Cartwheel galaxy, which is a starburst (Marston

& Appleton 1995; Mayya et al. 2005) and a collisional ring galaxy (Struck-Marcell & Higdon 1993; Struck et al. 1996; Mapelli et al. 2008a, 2008b), hosts a particularly large population of ULXs (~ 17 , Gao et al. 2003; Wolter & Trinchieri 2004; Wolter, Trinchieri & Colpi 2006). Recent studies (King 2004; Mapelli et al. 2008a) suggest that IMBHs can hardly account for all the ULXs observed in the Cartwheel. In fact, more than ~ 1000 IMBHs are required in order to produce the 17 observed ULXs. Such high number of IMBHs is hard to produce according to the most common theoretical models, such as the runaway collapse in young stellar clusters (Portegies Zwart & McMillan 2002), the repeated mergers of stellar-mass BHs in star clusters (Miller & Hamilton 2002) or the remnants of population III stars (Heger et al. 2003, hereafter H03). In this Letter we investigate an alternative scenario for the formation of massive BHs ($30 M_{\odot} \leq m_{\text{BH}} \leq 80 M_{\odot}$), which could account for most of the ULXs in the Cartwheel and in other metal-poor starburst galaxies. This model is based on the idea that low-metallicity ($Z \sim 0.05 Z_{\odot}$, i.e. approximately the metallicity of the Cartwheel, Fosbury & Hawarden 1977) massive stars ($\gtrsim 40 M_{\odot}$) lose only a small fraction of their mass due to stellar winds (Maeder 1992, hereafter M92; H03) and can directly collapse (Fryer 1999) into massive BHs ($30 M_{\odot} \leq m_{\text{BH}} \leq 80 M_{\odot}$). This scenario has already been suggested in previous studies (Pakull & Mirioni 2002; Zampieri et al. 2004; Soria et al. 2005; Swartz, Soria & Tennant 2008), which pointed out a correlation between

formation of ULXs and low-metallicity environments, and proposed that this may be connected with the influence of metallicity on the evolution of massive stars. The hypothesis that bright ULXs contain $\approx 30 - 90 M_\odot$ BHs formed in a low-metallicity environment is also considered in a companion investigation (Zampieri & Roberts 2009).

2 MODEL

According to numerical models (Fryer 1999; H03), a star which, at the end of its life, has a mass of $\geq 40 M_\odot$ is likely to directly collapse into a BH¹. In this case, the mass of the remnant BH is likely close to the final mass of the progenitor star, as no significant mass ejection is expected in the direct collapse. Massive stars with metallicity close to solar cannot have masses larger than $\sim 10 - 15 M_\odot$ at the end of their life, even if their initial mass was very large, as they are expected to lose a lot of mass due to stellar winds (H03; Meynet & Maeder 2003). Instead, massive stars with lower metallicity are less affected by stellar winds and retain a larger fraction of their initial mass. M92 shows that a star with metallicity $Z \sim 0.05 Z_\odot$ retains ~ 100 per cent of its initial mass m_{in} if $m_{\text{in}} \leq 40 M_\odot$, and $\sim 80 - 67$ per cent of m_{in} if $60 M_\odot \leq m_{\text{in}} \leq 120 M_\odot$. Thus, combining the results by M92 and by Fryer (1999), stars with metallicity $Z \lesssim 0.05 Z_\odot$ and initial mass $40 M_\odot \leq m_{\text{in}} \leq 120 M_\odot$ might end their life directly collapsing into BHs with mass $30 M_\odot \leq m_{\text{BH}} \leq 80 M_\odot$. Such BHs (that, in the following, we will dub simply as ‘massive BHs’) may be considered IMBHs, although close to the low-mass limit for IMBHs, and are sufficiently massive to power most of ULXs. If this model is correct, we can approximately estimate the total number of massive BHs (N_{BH}) which are formed by this process during a burst of star formation (SF), as

$$N_{\text{BH}} = A \int_{40 M_\odot}^{m_{\text{max}}} m^{-\alpha} dm, \quad (1)$$

where m_{max} is the maximum stellar mass (we assume $m_{\text{max}} = 120 M_\odot$) and α is the index of the initial mass function (IMF). A , the normalization constant, can be estimated as

$$A = \frac{\text{SFR } t_{\text{burst}}}{\int_{m_{\text{min}}}^{m_{\text{max}}} m^{1-\alpha} dm}, \quad (2)$$

where SFR is the SF rate during the burst, t_{burst} the duration of the burst and m_{min} the minimum stellar mass (we assume $m_{\text{min}} = 0.08 M_\odot$). Similarly, we can estimate the total mass of massive BHs (M_{BH}) as

$$M_{\text{BH}} = A \int_{40 M_\odot}^{m_{\text{max}}} m^{-\alpha} (mb + c) dm, \quad (3)$$

where $b = 0.54$ and $c = 15.59 M_\odot$ account for the mass losses due to stellar winds and have been derived by linearly fitting the values in table 1 of M92 for initial stellar masses $m_{\text{in}} \geq 40 M_\odot$. Once N_{BH} is known, we can estimate the upper limit (ϵ_{BH}) of the fraction of massive BHs which power

ULXs in a given galaxy at present, assuming that all the observed ULXs in this galaxy are powered by a massive BH:

$$\epsilon_{\text{BH}} = \frac{N_{\text{ULX}}}{N_{\text{BH}}}. \quad (4)$$

In order to check the robustness of this model, ϵ_{BH} can be compared with the fraction of massive BHs which are expected to power ULXs at present (ϵ_{exp}), derived combining recent dynamical (Blecha et al. 2006, hereafter B06) and binary-evolution (Patruno et al. 2005) models. Such models are completely independent and unrelated to the scenario presented in this Letter. In particular, B06 show that a massive BH with mass $\approx 100 M_\odot$ hosted in a young stellar cluster undergoes mass transfer from a companion star for a fraction $f_{\text{MT}} \sim 0.03$ of the life of the cluster². Patruno et al. (2005) show that only mass transfer between a massive BH and a star with mass $\geq 10 M_\odot$ is able to produce a persistent ULX, whereas, if the companion mass is lower ($2 M_\odot \leq m < 10 M_\odot$), the X-ray source is transient, with a very short burst (few days) every few months (Portegies Zwart, Dewi & Maccarone 2004). A transient source reaches ULX luminosities only during the burst phase (Portegies Zwart et al. 2004). Thus, ϵ_{exp} can be derived, on the basis to these models, as:

$$\epsilon_{\text{exp}} = f_{\text{MT}} \left(\int_{m_{\text{min}}}^{m_{\text{max}}} m^{-\alpha} dm \right)^{-1} \times \left(\int_{10 M_\odot}^{m_{\text{max}}} m^{-\alpha} dm + f_{\text{duty}} \int_{2 M_\odot}^{10 M_\odot} m^{-\alpha} dm \right), \quad (5)$$

where m_{min} and m_{max} are the same as adopted in eq. (2). f_{duty} represents the fraction of time which a transient source spends in its burst phase. In the following, we will assume $f_{\text{duty}} = 10^{-2}$, which is a reasonable upper limit (Portegies Zwart et al. 2004; King 2004). If ϵ_{BH} is close to ϵ_{exp} , this would indicate that our model provides reasonable results. We stress that this is a simple estimate of ϵ_{exp} , and has various limitations. First, the assumption that f_{duty} is constant is a simplification. On the other hand, there are still large uncertainties about the duty cycle and its dependence on the properties of the accreting system (Portegies Zwart et al. 2004). As we will show in the next Section, a different duty cycle does not affect significantly our estimates. Another limit of this model is the assumption that the massive BHs remain inside their parent cluster. Observations show that there is a displacement between some ULXs and the star clusters (e.g. Zezas et al. 2002). This might indicate that some massive BHs were ejected, together with their companion stars, from the parent clusters. In case of ejection, f_{MT} likely depends only on the evolution of the companion star (which cannot be exchanged with other stars) and is probably different from the estimates by B06. A new model would be required to quantify f_{MT} in case of ejection. This issue will be addressed in a forthcoming paper. However, the possible ejection of some BHs from the parent cluster does not affect the number of massive BHs which form in our scenario, as derived in eq. (1), and the corresponding value of ϵ_{BH} in eq. (4), but only the estimate of ϵ_{exp} in eq. (5).

¹ However, depending on the metallicity, stars which undergo a strong luminous-blue-variable phase end their life as neutron stars (see Belczynski, Kalogera & Bulik 2002 and references therein).

² The value of f_{MT} derived from B06 accounts at statistical level for all the companions which may undergo mass transfer (i.e. both main sequence and post-main sequence).

3 RESULTS FOR THE CARTWHEEL

The Cartwheel, which has a low metallicity ($Z \sim 0.05 Z_{\odot}$, measured in the nebulae of the outer ring which are forming stars right now, Fosbury & Hawarden 1977) and hosts a large number of ULXs (~ 17 , Wolter & Trinchieri 2004), appears the ideal candidate to check this model. First, let us estimate the approximate total number and mass of massive BHs which can form in the Cartwheel via such a mechanism, by using eqs. (1)–(3). The SFR in the Cartwheel is $\sim 20 M_{\odot} \text{ yr}^{-1}$ (Mayya et al. 2005). The time of the burst t_{burst} is probably the most uncertain among the quantities in eq. (2). Simulations show that ~ 100 Myr have elapsed from the galaxy interaction which produced the Cartwheel’s ring (Mapelli et al. 2008a). Thus, one can take $t_{\text{burst}} = 10^8$ yr as an upper limit. However, we are not interested in all the massive BHs, but only in those which can easily acquire a massive stellar companion, that is those which are still in the parent stellar cluster. Furthermore, in order to produce the persistent ULXs which have been detected in the Cartwheel (Wolter & Trinchieri 2004; Wolter et al. 2006), the parent star cluster should still host sufficiently massive stars. Thus, we also adopt $t_{\text{burst}} = 10^7$ yr, which is approximately the lifetime of a $15 M_{\odot}$ star. For the IMF in eq. (1) we consider two different cases: a Salpeter IMF ($\alpha = 2.35$, Salpeter 1955) and a Kroupa IMF, which is relatively top-heavy ($\alpha = 1.3$ if $m \leq 0.5 M_{\odot}$ and $\alpha = 2.3$ for larger masses, Kroupa 2001).

The results from eqs. (1) and (3) are the following (see Table 1). Assuming $t_{\text{burst}} = 10^8$ yr, the total number of massive BHs is $N_{\text{BH}} = 1.2 \times 10^6$ and $N_{\text{BH}} = 2.4 \times 10^6$ for the Salpeter and the Kroupa IMF, respectively. The total number of massive BHs born during the last 10^7 yr is $N_{\text{BH}} = 1.2 \times 10^5$ and $N_{\text{BH}} = 2.4 \times 10^5$ for the Salpeter and the Kroupa IMF, respectively. These numbers are quite higher than those predicted by the runaway collapse (Portegies Zwart & McMillan 2002). In fact, even assuming that each massive ($\gtrsim 10^4 M_{\odot}$) young cluster produces one or even two IMBHs (Gürkan, Fregeau & Rasio 2006) via runaway collapse (which is an upper limit, see Gvaramadze, Gualandris & Portegies Zwart 2008), $\sim 10^5$ massive young clusters should form during the starburst, in order to generate the same number of IMBHs. Our model does not suffer from such limitations, as it predicts that more than one massive BH may form in the same cluster and that massive BHs can form also outside clusters. For a Salpeter (Kroupa) IMF, the total mass of massive BHs which are born during the last 10^7 yr, and thus are able to produce a ULX, is $M_{\text{BH}} \sim 6.2 \times 10^6 M_{\odot}$ ($M_{\text{BH}} \sim 1.23 \times 10^7 M_{\odot}$). The average mass of a single massive BH is $\langle m_{\text{BH}} \rangle = 50.2 M_{\odot}$ and $\langle m_{\text{BH}} \rangle = 50.4 M_{\odot}$, using the Salpeter and the Kroupa IMF, respectively.

Since the observed ULXs in the Cartwheel are 17, from eq. (4) we obtain $\epsilon_{\text{BH}} = 1.4 \times 10^{-4}$ and $\epsilon_{\text{BH}} = 6.9 \times 10^{-5}$ for the Salpeter and the Kroupa IMF, respectively, if $t_{\text{burst}} = 10^7$ yr is assumed. Let us see now how ϵ_{BH} compares with ϵ_{exp} . From eq. (5) we get $\epsilon_{\text{exp}} = 4.6 \times 10^{-5}$ and $\epsilon_{\text{exp}} = 2.4 \times 10^{-4}$ for a Salpeter and a Kroupa IMF, respectively. We stress that most of the contribution in eq. (5) comes from the persistent ULXs (those with a companion mass larger than $10 M_{\odot}$). In fact, the value of ϵ_{exp} once we neglect the transient sources is $\epsilon_{\text{exp}} = 4.3 \times 10^{-5}$ and $\epsilon_{\text{exp}} = 2.3 \times 10^{-4}$

Table 1. Results for the Cartwheel (assuming $t_{\text{burst}} = 10^7$ yr).

	Salpeter	Kroupa
N_{BH}	1.2×10^5	2.4×10^5
$M_{\text{BH}} (M_{\odot})$	6.2×10^6	1.23×10^7
ϵ_{BH}	1.4×10^{-4}	6.9×10^{-5}
ϵ_{exp}	4.6×10^{-5}	2.4×10^{-4}

for a Salpeter and a Kroupa IMF, respectively. Thus, a lower value of f_{duty} does not affect our results. The main conclusion is that ϵ_{BH} and ϵ_{exp} are quite similar one to the other. In particular, ϵ_{BH} is ~ 3 times higher than ϵ_{exp} assuming a Salpeter IMF, and ~ 3 lower than ϵ_{exp} assuming a Kroupa IMF (see Table 1). Thus, the model of massive BH formation from direct collapse of low-metallicity massive stars may be able to explain the ULXs observed in the Cartwheel.

4 COMPARISON WITH OTHER GALAXIES

The model presented in this Letter works quite well for the Cartwheel (Section 3). Is it possible to check it for other galaxies? In Table 2 we have listed a small sample of galaxies which have interesting properties for this study. This sample includes galaxies which host at least one ULX and for which metallicity measurements are available (apart from the case of UGC 7069, for which X-ray measurements are currently unavailable, but which is quite similar to the Cartwheel for many aspects). In particular, the sample includes three of the best studied ring galaxies (Cartwheel, AM 0644-741 and UGC 7069), seven galaxies with a large number of ULXs ($\gtrsim 2$ ULXs with $L_X \gtrsim 10^{39} \text{ erg s}^{-1}$) and the dwarf irregular galaxy Holmberg II (HoII), which hosts a single, very bright ULX ($L_X \gtrsim 10^{40} \text{ erg s}^{-1}$, Dewangan et al. 2004).

Fig. 1 shows N_{ULX} versus the metallicity Z (top panel) and the SFR (bottom panel) for the galaxies of our sample (filled and open circles). The galaxies indicated with open circles in Fig. 1 do not have metallicity measurements suitable for this study. In fact, the value of the metallicity needed in our model is the one the galaxy had before the beginning of the SF burst which produced the massive BHs. In the case of AM 0644-741 the metallicity measurement comes from the bulge (Giordano et al. in preparation), which is dominated by old stars, whereas there are no measurements for the star forming outer ring. In the case of NGC 4485/4490, the value of Z quoted in Table 2 is likely an upper limit, as the method used by Pilyugin & Thuan (2007) does not work for metallicities $Z \lesssim 0.4$. Finally, NGC 3256 has already undergone a strong burst of SF and it is difficult to find HII regions which are still unpolluted in this galaxy (Lípari et al. 2000), whereas in ring galaxies or in interacting galaxies it is relatively easy to find regions where the SF just started. The filled circle for NGC 4559, corresponding to $Z = 0.3 Z_{\odot}$, comes from X-ray measurements (Cropper et al. 2004), and the error bar comes from the estimate ($0.2 \lesssim Z/Z_{\odot} \lesssim 0.4$, Soria et al. 2005) obtained with the Padua stellar tracks (STs). However, when the Geneva STs are used instead of the Padua STs, the estimated metallicity of NGC 4559 is quite lower ($0.05 \lesssim Z/Z_{\odot} \lesssim 0.2$, Soria et al. 2005). The ab-

Table 2. Properties of the galaxies in our sample.

Galaxy	SFR ($M_{\odot} \text{ yr}^{-1}$)	Z (Z_{\odot}) ^a	N_{ULX}	references ^b
Cartwheel	20	0.05 (outer ring spectra)	17	1, 2, 3
AM 0644–741	3	0.45 (bulge spectra)	9	4, 5
UGC 7069	13.4	0.08 ± 0.014 (spectra)	–	6
Antennae	7.1	0.04 (X-ray)	8	7, 8, 9
NGC 4485/4490	1.0	< 0.4 (SDSS spectra)	8	7, 10, 11
NGC 3395/3396	–	$0.07^{+0.03}_{-0.01}$ (NGC 3395, X-ray), $0.05^{+0.04}_{-0.01}$ (NGC 3396, X-ray)	7	12
The Mice (Arp 242)	8.8	0.3 (X-ray)	5	13, 14
NGC 3256	44	1.0 (spectra of HII regions)	14	7, 15, 16
NGC 1313	1.4	0.1–0.2 (spectra)	2	17, 18, 19
NGC 4559	–	0.05 – 0.2 (Geneva STs), 0.2 – 0.4 (Padua STs), $0.3^{+0.3}_{-0.2}$ (X-ray)	2	20
Holmberg II	0.07–0.1	0.1 (spectra)	1	21, 22

^a The metallicities collected in this Table come from different measurement methods. For each entry we indicate the type of measurement within parentheses. See the references for details. ^b 1. Mayya et al. (2005); 2. Fosbury & Hawarden (1977); 3. Wolter & Trinchieri (2004); 4. Higdon & Wallin (1997); 5. Giordano et al. in preparation; 6. Ghosh & Mapelli (2008); 7. Grimm, Gilfanov & Sunyaev (2003) and references therein; 8. Fabbiano et al. (2004); 9. Fabbiano, Zezas & Murray (2001); 10. Pilyugin & Thuan (2007); 11. Fridriksson et al. (2008); 12. Brassington, Read & Ponman (2005); 13. Hunter et al. (1986); 14. Read (2003); 15. L  p  ri et al. (2000); 16. Lira et al. (2002); 17. Ryder & Dopita (1994); 18. Ryder (1993); 19. Colbert et al. (1995); 20. Soria et al. (2005) and references therein; 21. Walter et al. (2007); 22. Dewangan et al. (2004).

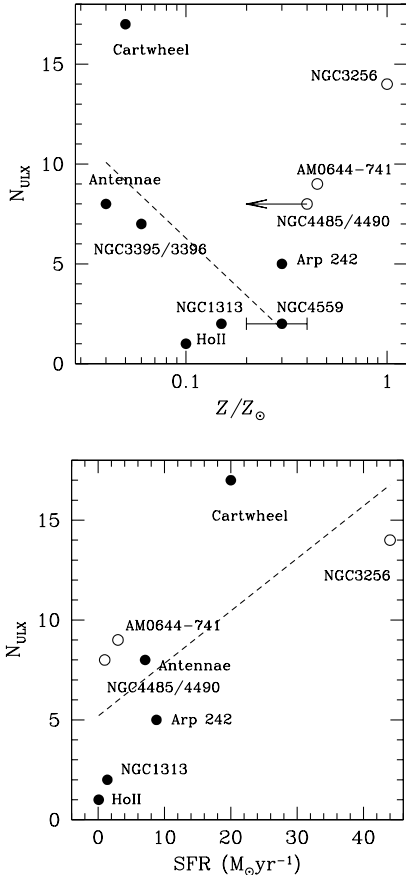


Figure 1. Top (bottom) panel: number of ULXs versus metallicity (SFR) for the galaxies listed in Table 2. The open circles correspond to NGC 3256, AM 0644–741 and NGC 4485/4490 (see Section 4), the filled circles to all the other galaxies listed in Table 2. Dashed lines: linear fits.

sense of error bars for most of metallicities in the top panel of Fig. 1 means only that the measurements are highly uncertain and/or that there are no estimates of the error (see Table 2 and references therein for details). In general, the metallicity measurements reported in Table 2 are uncertain and/or obtained with very different methods, from spectral analysis to X-ray data. Thus, they are quite difficult to compare with each other and the top panel of Fig. 1 must be considered *cum grano salis*. New, homogeneous metallicity measurements are required, in order to test a possible relation between N_{ULX} and Z .

Taking into account all these strong *caveats*, the top panel of Fig. 1 suggests a correlation between N_{ULX} and Z . If we exclude AM 0644–741, NGC 3256 and NGC 4485/4490 for the reasons mentioned above, we find a correlation:

$$N_{\text{ULX}} = \beta \log_{10}(Z/Z_{\odot}) + \gamma, \quad (6)$$

where $\beta = -9.53$ and $\gamma = -3.25$. The correlation is shown by the dashed line in the top panel of Fig. 1. The bottom panel of Fig. 1 shows that there is an evident correlation between SFR and N_{ULX} for our sample, in agreement with previous studies (Grimm, Gilfanov & Sunyaev 2003; Gilfanov, Grimm & Sunyaev 2004a, 2004b, and references therein). Excluding NGC 3395/3396 and NGC 4559, for which there are no estimates of the global SFR, we obtain the following linear relation.

$$N_{\text{ULX}} = \delta \text{SFR} [M_{\odot} \text{ yr}^{-1}] + \zeta, \quad (7)$$

where $\delta = 0.26$ and $\zeta = 5.19$. The correlation is shown with a dashed line in the bottom panel of Fig. 1.

In conclusion, our sample confirms the existence of a correlation between SFR and N_{ULX} and suggests a possible anti-correlation between Z and N_{ULX} . The fact that galaxies which host a large number of ULXs have often low metallicity indirectly supports the scenario proposed in Sections 2 and 3. In particular, three of the considered galaxies (i.e. the Cartwheel, the Antennae and NGC 3395/3396) host a

large number of ULXs ($N_{\text{ULX}} \geq 7$) and have very low metallicity ($Z \sim 0.06 Z_{\odot}$). Thus, we can apply also to the Antennae and to NGC 3395/3396 the method³ used for the Cartwheel in Section 3. For the Antennae, adopting a SFR of $7.1 M_{\odot} \text{ yr}^{-1}$, $N_{\text{ULX}} = 8$ (Table 2) and $t_{\text{burst}} = 10^7 \text{ yr}$, we obtain $\epsilon_{\text{BH}} = 1.8 \times 10^{-4}$ and $\epsilon_{\text{BH}} = 9 \times 10^{-5}$ for the Salpeter and the Kroupa IMF, respectively. In the case of NGC 3395/3396, the SFR is uncertain. Adopting a SFR of $6 M_{\odot} \text{ yr}^{-1}$ (derived from the correlation between SFR and X-ray luminosity in eq. 14 of Ranalli, Comastri & Setti 2003), $N_{\text{ULX}} = 7$ (Table 2) and $t_{\text{burst}} = 10^7 \text{ yr}$, we obtain $\epsilon_{\text{BH}} = 1.9 \times 10^{-4}$ and $\epsilon_{\text{BH}} = 9 \times 10^{-5}$ for the Salpeter and the Kroupa IMF, respectively. These values are similar to those obtained for the Cartwheel and to the estimates of ϵ_{exp} reported in Table 1. Thus, our method gives reasonable results not only for the Cartwheel but also for other interacting galaxies.

We stress that the fact that many galaxies which host ULXs (e.g. NGC 4485/4490, Arp 242, NGC 1313, Holmberg II, etc.) have metallicity (slightly) higher than that of the Cartwheel does not contradict our scenario for massive BH formation. In fact, the metallicity we measure now is not necessarily the same as the metallicity of the parent molecular cloud, where the massive BHs formed. It is likely that the metallicity we measure now has been partially polluted by the episode of SF which generated the massive BHs. Only for the collisional ring galaxies, where the dynamical evolution of the ring is strongly coupled to the SF history, it is relatively easy to measure the metallicity of the pre-starburst gas (i.e. the gas which resides in the outer ring).

5 CONCLUSIONS

Low-metallicity ($Z \lesssim 0.05 Z_{\odot}$) massive ($\gtrsim 40 M_{\odot}$) stars might end their life by directly collapsing into massive BHs ($30 \lesssim m_{\text{BH}}/M_{\odot} \lesssim 80$, M92; H03). Such massive BHs might power most of the observed ULXs in low-metallicity galaxies (such as the Cartwheel and the Antennae). In support of this scenario, the data listed in Table 2 suggest an anti-correlation between the number of ULXs and the metallicity of the host galaxy.

However, many open questions and uncertainties remain. First of all, the final stellar masses reported by M92 are still debated: a similar study by Portinari, Chiosi & Bressan (1998) finds sensibly lower masses. Belczynski, Sadowski & Rasio (2004) also find lower initial masses for the BHs ($\sim 20 - 30 M_{\odot}$), but investigate the possibility of increasing the mass of the BH (up to $\sim 80 M_{\odot}$) via binary mergers. Furthermore, the models considered in M92 and in Fryer (1999) neglect some important effect, such as the rotation and the possible binarity of the progenitor. Accounting for the binarity of the progenitor likely induces a factor of 2 uncertainty in our results. In addition, the model considered

here does not include the possibility of pair instability supernovae (PISs). PISs probably do not play a role for stars with $Z \sim 0.05 Z_{\odot}$ (H03). On the other hand, even assuming (as a strong upper limit) that all stars with mass $\geq 100 M_{\odot}$ do not leave any remnant, due to a PIS, our estimates of ϵ_{BH} change by less than 10 per cent.

The lack, paucity or uncertainty in the metallicity measurements make hard to test our model. Moreover, the metallicity needed in our model is that of the molecular clouds before the pollution from the first generation of supernovae, as very massive stars ($> 40 M_{\odot}$) collapse into BHs before the explosion of the first supernovae in the parent cluster. Thus, the metallicity measured today is likely higher than the value we should consider in our model. Only for some types of galaxies, such as the ring galaxies, where the SF history has a clear connection with the geometry of the system, it is possible to measure a pre-starburst value of Z , suitable for our purposes.

ACKNOWLEDGMENTS

We thank E. Ripamonti, R. Decarli, A. Wolter, P. Englmaier, L. Giordano and A. Bressan for useful discussions and we acknowledge the anonymous referee for his helpful comments. MM acknowledges support from the Swiss National Science Foundation, project number 200020-109581/1. MC and LZ acknowledge financial support from INAF through grant PRIN-2007-26.

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³ At present we cannot apply our method to galaxies with $Z \gtrsim 0.06 Z_{\odot}$, because we do not know which is the minimum initial mass for which stars with metallicity $0.5 \gtrsim Z/Z_{\odot} \gtrsim 0.06$ end their life by directly collapsing into BHs. However, it is likely that massive BHs are formed also by stars with metallicity slightly higher than $0.06 Z_{\odot}$. Further studies are needed, to constrain the upper limit of stellar metallicity for which massive BHs can form.

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